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Electric Power Utilization

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7.1 Metering of Electric Power and Energy

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Electrical metering deals with two basic quantities: *energy* and *power*. Energy is equivalent to work. Power is the rate of doing work. Power applied (or consumed) for any length of time is energy. In mathematical terms, power integrated over time is energy. The basic electrical unit of energy is the watthour. The basic unit of power is the watt. The watthour meter measures energy (in watthours), while the wattmeter measures the rate of energy, power (in watthours per hour or simply watts). For a constant power level, power multiplied by time is energy. For example, a watthour meter connected for two hours in a circuit using 500 watts (500 watthours per hour) will register 1000 watthours.

The Electromechanical Meter

The electromechanical watthour meter is basically a very specialized electric motor, consisting of

- A *stator* and a *rotor* that together produce torque
- A *brake* that creates a counter torque
- A *register* to count and display the revolutions of the rotor

Single Stator Electromechanical Meter

A two-wire single stator meter is the simplest electromechanical meter. The single stator consists of two electromagnets. One electromagnet is the potential coil connected between the two circuit conductors. The other electromagnet is the current coil connected in series with the load current. Figure 7.1 shows the major components of a single stator meter.

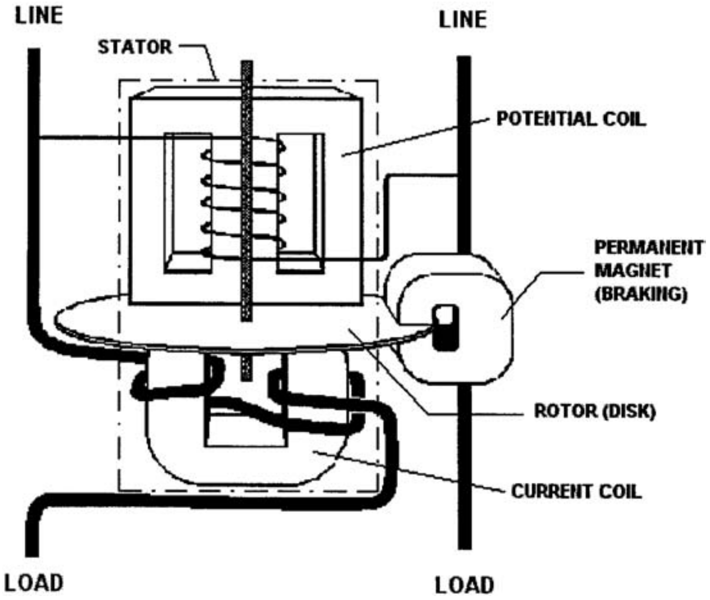


FIGURE 7.1 Main components of electromechanical meter.

The electromagnetic fields of the current coil and the potential coil interact to generate torque on the rotor of the meter. This torque is proportional to the product of the source voltage, the line current, and the cosine of the phase angle between the two. Thus, the torque is also proportional to the power in the metered circuit.

The device described so far is incomplete. In measuring a steady power in a circuit, this meter would generate constant *torque* causing steady acceleration of the rotor. The rotor would spin faster and faster until the torque could no longer overcome friction and other forces acting on the rotor. This ultimate speed would not represent the level of power present in the metered circuit.

To address these problems, designers add a permanent magnet whose magnetic field acts on the rotor. This field interacts with the rotor to cause a *counter torque* proportional to the speed of the rotor. Careful design and adjustment of the magnet strength yields a meter that rotates at a *speed* proportional to power. This speed can be kept relatively slow. The product of the rotor speed and time is revolutions of the rotor. The revolutions are proportional to energy consumed in the metered circuit. One revolution of the rotor represents a fixed number of watthours. The revolutions are easily converted via mechanical gearing or other methods into a display of watthours or, more commonly, kilowatthours.

Blondel's Theorem

Blondel's theorem of polyphase metering describes the measurement of power in a polyphase system made up of an arbitrary number of conductors. The theorem provides the basis for correctly metering power in polyphase circuits. In simple terms, Blondel's theorem states that the total power in a system of (N) conductors can be properly measured by using (N) wattmeters or watt-measuring elements. The elements are placed such that one current coil is in each of the conductors and one potential coil is connected between each of the conductors and some common point. If this common point is chosen to be one of the (N) conductors, there will be zero voltage across one of the measuring element potential coils. This element will register zero power. *Therefore, the total power is correctly measured by the remaining (N – 1) elements.*

In application, this means that to accurately measure the power in a four-wire three-phase circuit (N = 4), the meter must contain (N – 1) or three measuring elements. Likewise, for a three-wire three-phase circuit

(N = 3), the meter must contain two measuring elements. There are meter designs available that, for commercial reasons, employ less than the minimum number of elements (N – 1) for a given circuit configuration. These designs depend on *balanced* phase voltages for proper operation. Their accuracy suffers as voltages become unbalanced.

The Electronic Meter

Since the 1980s, meters available for common use have evolved from (1) electromechanical mechanisms driving mechanical, geared registers to (2) the same electromechanical devices driving electronic registers to (3) totally electronic (or solid state) designs. All three types remain in wide use, but the type that is growing in use is the solid state meter.

The addition of the electronic register to an electromechanical meter provides a digital display of energy and demand. It supports enhanced capabilities and eliminates some of the mechanical complexity inherent in the geared mechanical registers.

Electronic meters contain no moving mechanical parts — rotors, shafts, gears, bearings. They are built instead around large-scale integrated circuits, other solid state components, and digital logic. Such meters are much more closely related to computers than to electromechanical meters.

The operation of an electronic meter is very different than that described in earlier sections for an electromechanical meter. Electronic circuitry samples the voltage and current waveforms during each electrical cycle and converts these samples to digital quantities. Other circuitry then manipulates these values to determine numerous electrical parameters, such as kW, kWh, kvar, kvarh, kQ, kQh, power factor, kVA, rms current, rms voltage.

Various electronic meter designs also offer some or all of the following capabilities:

- **Time of use (TOU)**. The meter keeps up with energy and demand in multiple daily periods. (See section on Time of Use Metering.)
- **Bi-directional**. The meter measures (as separate quantities) energy delivered to and received from a customer. This feature is used for a customer that is capable of generating electricity and feeding it back into the utility system.
- **Loss compensation**. The meter can be programmed to automatically calculate watt and var losses in transformers and electrical conductors based on defined or tested loss characteristics of the transformers and conductors. It can internally add or subtract these calculated values from its measured energy and demand. This feature permits metering to be installed at the most economical location. For instance, we can install metering on the secondary (e.g., 4 kV) side of a customer substation, even when the contractual service point is on the primary (e.g., 110 kV) side. The 4 kV metering installation is much less expensive than a corresponding one at 110 kV. Under this situation, the meter compensates its secondary-side energy and demand readings to simulate primary-side readings.
- **Interval data recording**. The meter contains solid state memory in which it can record up to several months of interval-by-interval data. (See section on Interval Data Metering.)
- **Remote communications**. Built-in communications capabilities permit the meter to be interrogated remotely via telephone, radio, or other communications media.
- **Diagnostics**. The meter checks for the proper voltages, currents, and phase angles on the meter conductors. (See section on Site Diagnostic Meter.)
- **Power quality**. The meter can measure and report on momentary voltage or current variations and on harmonic conditions.

Note that many of these features are available only in the more advanced (and expensive) models of electronic meters.

As an example of the benefits offered by electronic meters, consider the following two methods of metering a large customer who is capable of generating and feeding electricity back to the utility. In this example, the metering package must perform these functions:

Measure kWh delivered to the customer
Measure kWh received from the customer
Measure kvarh delivered
Measure kvarh received
Measure kW delivered
Measure kW received
Compensate received quantities for transformer losses
Record the measured quantities for each demand interval

Method A. (2) kW/kWh electromechanical meters with pulse generators (one for delivered, one for received)
(2) kWh electromechanical meters with pulse generators (to measure kvarh)
(2) Phase shifting transformers (used along with the kWh meters to measure kvarh)
(2) Transformer loss compensators
(1) Pulse data recorder
Method B. (1) Electronic meter

Obviously, the electronic installation is much simpler. In addition, it is less expensive to purchase and install and is easier to maintain.

Benefits common to most solid state designs are high accuracy and stability. Another less obvious advantage is in the area of error detection. When an electromechanical meter develops a serious problem, it may produce readings in error by any arbitrary amount. An error of 10%, 20%, or even 30% can go undetected for years, resulting in very large over- or under-billings. However, when an electronic meter develops a problem, it is more likely to produce an obviously bad reading (e.g., all zeroes; all 9s; a demand 100 times larger than normal; or a blank display). This greatly increases the likelihood that the error will be noticed and reported soon after it occurs. The sooner such a problem is recognized and corrected, the less inconvenience and disruption it causes to the utility and to the customer.

Multifunction Meter

Multifunction or *extended function* refers to a meter that can measure reactive or apparent power (e.g., kvar or kVA) in addition to real power (kW). By virtue of their designs, many electronic meters inherently measure the quantities and relationships that define reactive and apparent power. It is a relatively simple step for designers to add meter intelligence to calculate and display these values.

Voltage Ranging and Multiform Meter

Electronic meter designs have introduced many new features to the watthour metering world. Two features, typically found together, offer additional flexibility, simplified application, and opportunities for reduced meter inventories for utilities.

- *Voltage ranging* – Many electronic meters incorporate circuitry that can sense the voltage level of the meter input signals and adjust automatically to meter correctly over a wide range of voltages. For example, a meter with this capability can be installed on either a 120 volt or 277 volt service.
- *Multiform* – Meter form refers to the specific combination of voltage and current signals, how they are applied to the terminals of the meter, and how the meter uses these signals to measure power and energy. For example, a Form 15 meter would be used for self-contained application on a 120/240 volt 4-wire delta service, while a Form 16 meter would be used on a self-contained 120/208 volt 4-wire wye service. A *multiform* 15/16 meter can work interchangeably on either of these services.

Site Diagnostic Meter

Newer meter designs incorporate the ability to measure, display, and evaluate the voltage and current magnitudes and phase relationships of the circuits to which they are attached. This capability offers important advantages:

- At the time of installation or reinstallation, the meter analyzes the voltage and current signals and determines if they represent a recognizable service type.
- Also at installation or reinstallation, the meter performs an initial check for wiring errors such as crossed connections or reversed polarities. If it finds an error, it displays an error message so that corrections can be made.
- Throughout its life, the meter continuously evaluates voltage and current conditions. It can detect a problem that develops weeks, months, or years after installation, such as tampering or deteriorated CT or VT wiring.
- Field personnel can switch the meter display into diagnostic mode. It will display voltage and current magnitudes and phase angles for each phase. This provides a quick and very accurate way to obtain information on service characteristics.

If a diagnostic meter detects any error that might affect the accuracy of its measurements, it will lock its display in error mode. The meter continues to make energy and demand measurements in the background. However, these readings cannot be retrieved from the meter until the error is cleared. This ensures the error will be reported the next time someone tries to read the meter.

Special Metering

Demand Metering

What is Demand?

Electrical energy is commonly measured in units of kilowatthours. Electrical power is expressed as kilowatthours per hour or, more commonly, kilowatts.

Demand is defined as power averaged over some specified period. Figure 7.2 shows a sample power curve representing instantaneous power. In the time interval shown, the integrated area under the power curve represents the energy consumed during the interval. This energy, divided by the length of the interval (in hours) yields "demand." In other words, the demand for the interval is that value of power that, if held constant over the interval, would result in an energy consumption equal to that energy the customer actually used.

Demand is most frequently expressed in terms of real power (kilowatts). However, demand may also apply to reactive power (kilovars), apparent power (kilovolt-amperes), or other suitable units. Billing for demand is commonly based on a customer's maximum demand reached during the billing period.

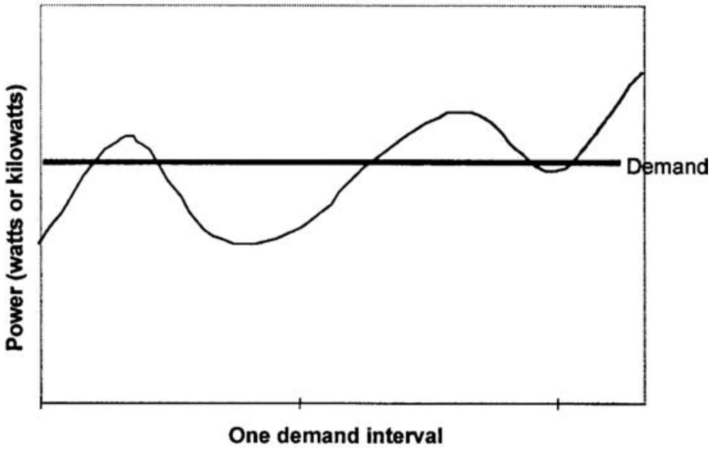


FIGURE 7.2 Instantaneous power vs. demand.

Why is Demand Metered?

Electrical conductors and transformers needed to serve a customer are selected based on the expected maximum demand for the customer. The equipment must be capable of handling the maximum levels of voltages and currents needed by the customer. A customer with a higher maximum demand requires a greater investment by the utility in equipment. Billing based on energy usage alone does not necessarily relate directly to the cost of equipment needed to serve a customer. Thus, energy billing alone may not equitably distribute to each customer an appropriate share of the utility's costs of doing business.

For example, consider two commercial customers with very simple electricity needs. Customer A has a demand of 25 kW and operates at this level 24 hours per day. Customer B has a maximum demand of 100 kW but operates at this level only 4 hours per day. For the remaining 20 hours of the day, "B" operates at a 10 kW power level.

$$\text{"A" uses } 25\text{ kW} \times 24\text{ hr} = 600\text{ kWh per day}$$

$$\text{"B" uses } (100\text{ kW} \times 4\text{ hr}) + (10\text{ kW} \times 20\text{ hr}) = 600\text{ kWh per day}$$

Assuming identical billing rates, each customer would incur the same energy costs. However, the utility's equipment investment will be larger for Customer B than for Customer A. By implementing a charge for demand as well as energy, the utility would bill Customer A for a maximum demand of 25 kW and Customer B for 100 kW. "B" would incur a larger total monthly bill, and each customer's bill would more closely represent the utility's cost to serve.

Integrating Demand Meters

By far the most common type of demand meter is the integrating demand meter. It performs two basic functions. First, it measures the *average* power during each *demand interval*. (Common demand interval lengths are 15, 30, or 60 min.) The meter makes these measurements interval-by-interval throughout each day. Second, it retains the maximum of these interval measurements.

The demand calculation function of an electronic meter is very simple. The meter measures the energy consumed during a demand interval, then multiplies by the number of demand intervals per hour. In effect, it calculates the energy that would be used if the rate of usage continued for one hour. The following table illustrates the correspondence between energy and demand for common demand interval lengths.

TABLE 7.1 Energy/Demand Comparisons

Demand Interval	Intervals per Hour	Energy During Demand Interval	Resulting Demand
60 min	1	100 kWh	100 kW
30 min	2	50 kWh	100 kW
15 min	4	25 kWh	100 kW

After each measurement, the meter compares the new demand value to the stored *maximum demand*. If the new value is greater than that stored, the meter replaces the stored value with the new one. Otherwise, it keeps the previously stored value and discards the new value. The meter repeats this process for each interval. At the end of the billing period, the utility records the maximum demand, then resets the stored *maximum demand* to zero. The meter then starts over for the new billing period.

Time of Use Metering

A time of use (TOU) meter measures and stores energy (and perhaps demand) for multiple periods in a day. For example, a service rate might define one price for energy used between the hours of 12 noon and 6 P.M. and another rate for that used outside this period. The TOU meter will identify the hours from 12 noon until 6 P.M. as "Rate 1." All other hours would be "Rate 2." The meter will maintain separate measurements of Rate 1 energy (and demand) and Rate 2 energy (and demand) for the entire billing period. Actual TOU service rates can be much more complex than this example, including features such as

- more than two periods per day,
- different periods for weekends and holidays, and
- different periods for different seasons of the year.

A TOU meter depends on an internal clock/calendar for proper operation. It includes battery backup to maintain its clock time during power outages.

Interval Data Metering

The standard method of gathering billing data from a meter is quite simple. The utility reads the meter at the beginning of the billing period and again at the end of the billing period. From these readings, it determines the energy and maximum demand for that period. This information is adequate to determine the bills for the great majority of customers. However, with the development of more complex service rates and the need to study customer usage patterns, the utility sometimes wants more detail about how a customer uses electricity. One option would be to read the meter daily. That would allow the utility to develop a day-by-day pattern of the customer's usage. However, having someone visit the meter site every day would quickly become very expensive. What if the meter could record usage data every day? The utility would have more detailed usage data, but would only have to visit the meter when it needed the data, for instance, once per month. And if the meter is smart enough to do that, why not have it record data even more often, for instance every hour?

In very simple terms, this is what *interval data metering* does. The interval meter includes sufficient circuitry and intelligence to record usage multiple times per hour. The length of the recording interval is programmable, often over a range from 1 to 60 minutes. The meter includes sufficient solid state memory to accumulate these interval readings for a minimum of 30 days at 15-minute intervals. Obviously, more frequent recording times reduce the days of storage available.

A simple kWh/kW recording meter typically records one set of data representing kWh. This provides the detailed usage patterns that allow the utility to analyze and evaluate customer "load profiles" based on daily, weekly, monthly, or annual bases. An extended function meter is commonly programmed to record two channels of data, e.g., kWh and kvarh. This provides the additional capability of analyzing customers' power factor patterns over the same periods. Though the meter records information in energy units (kWh or kvarh), it is a simple matter to convert this data to equivalent demand (kW or kvar). Since demand represents energy per unit time, simply divide the energy value for one recorder interval by the length of the interval (in hours). If the meter records 16.4 kWh in a 30-minute period, the equivalent demand for that period is 16.4 kWh/(0.5 hours) = 32.8 kW.

A sample 15-minute interval load shape for a 24-hour period is shown in the graph in Fig. 7.3. The minimum demand for that period was 10.5 kW, occurring during the interval ending at 04:30. The maximum demand was 28.7 kW, occurring during the interval ending at 15:15, or 3:15 P.M.

Pulse Metering

Metering pulses are signals generated in a meter for use outside the meter. Each pulse represents a discrete quantity of the metered value, such as kWh, kVAh, or kvarh. The device receiving the pulses determines the energy or demand at the meter by counting the number of pulses occurring in some time interval. A pulse is indicated by the transition (e.g., open to closed) of the circuit at the meter end. Pulses are commonly transmitted on small conductor wire circuits. Common uses of pulses include providing signals to

- customer's demand indicator
- customer's energy management system
- a *totalizer* (see section on Totalized Metering)

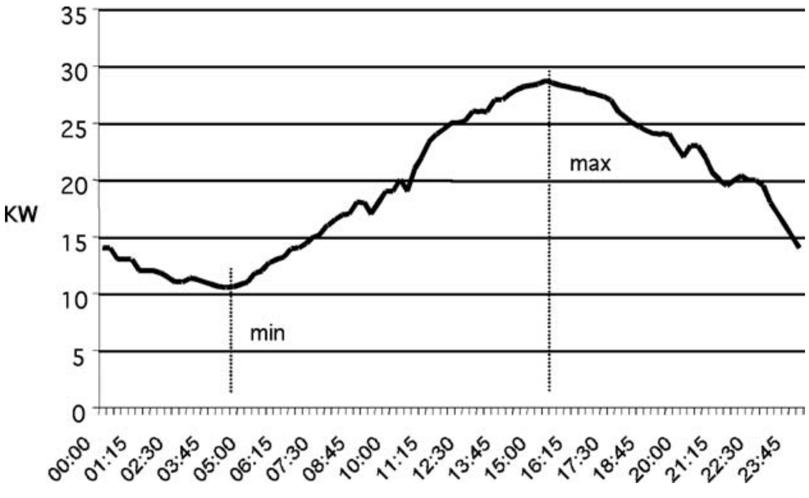


FIGURE 7.3 Graph of interval data.

- a metering data recorder
- a telemetering device that converts the pulses to other signal forms (e.g., telephone line tones or optical signals) for transmission over long distances

Pulse metering is installed when customer service requirements, equipment configurations, or other special requirements exceed the capability of conventional metering. Pulse metering is also used to transmit metered data to a remote location.

Recording Pulses

A meter pulse represents a quantity of energy, not power. For example, a pulse is properly expressed in terms of watthours (or kWh) rather than watts (or kW). A pulse recorder will associate time with pulses as it records them. If set up for a 15-minute recording interval, the recorder counts pulses for 15 min, then records that number of pulses. It then counts pulses for the next 15 min, records that number, and so on, interval after interval, day after day. It is a simple matter to determine the number of pulses recorded in a chosen length of time. Since the number of pulses recorded represents a certain amount of energy, simply divide this energy by the corresponding length of time (in hours) to determine average power for that period.

Example: For a metering installation, we are given that each pulse represents 2400 watthours or 2.4 kWh. In a 15-minute period, we record 210 pulses. What is the corresponding energy (kWh) and demand (kW) during this 15-minute interval?

Total energy in interval = 2.4 kWh per pulse × 210 pulses
= 504 kWh
Demand = Energy/Time = 504 kWh/0.25 hour
= 2016 kW

Often, a customer asks for the demand value of a pulse, rather than the energy value. The demand value is dependent on demand interval length. The demand pulse value is equal to the energy pulse value divided by the interval length in hours.

For the previous example, the kW pulse value would be:

2.4 kWh per pulse/0.25 hours = 9.6 kW per pulse

and the resulting demand calculation is:

Demand = 9.6 kW per pulse × 210 pulses
= 2016 kW

Remember, however, that a pulse demand value is meaningful only for a specific demand interval. In the example above, counting pulses for any period other than 15 minutes and then applying the kW pulse value will yield incorrect results for demand.

Pulse Circuits

Pulse circuits commonly take two forms (Fig. 7.4):

- *Form A*, a two-wire circuit where a switch toggles between closed and open. Each transition of the circuit (to open or to closed) represents one pulse.
- *Form C*, a three-wire circuit where the switch flip-flops. Each transition (from closed on one side to closed on the other) represents one pulse.

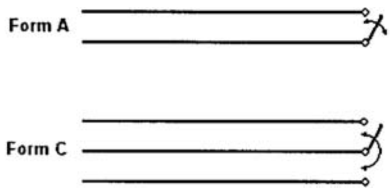


FIGURE 7.4 Pulse circuits.

Use care in interpreting pulse values for these circuits. The value will normally be expressed per *transition*. With Form C circuits, a transition is a change from closed on the first side to closed on the second side. Most receiving equipment interprets this properly. However, with Form A circuits, the transition is defined as a change from open to closed or from closed to open. An initially open Form A circuit that closes, then opens has undergone two (2) transitions. If the receiving equipment counts only circuit closures, it will record only half of the actual transitions. This is not a problem if the applicable pulse value of the Form A circuit is *doubled* from the rated pulse weight per transition. For example, if the value of a Form A meter pulse is 3.2 kWh per transition, the value needed for a piece of equipment that only counted circuit closures would be 3.2 × 2 = 6.4 kWh per pulse.

Totalized Metering

Totalized metering refers to the practice of combining data to make multiple service points look as if they were measured by a single meter. This is done by combining two or more sets of data from separate meters to generate data equivalent to what would be produced by a single "virtual meter" that measured the total load. This combination can be accomplished by:

- Adding recorded interval data from multiple meters, usually on a computer
- Adding (usually on-site) meter pulses from multiple meters by a special piece of metering equipment known as a totalizer
- Paralleling the secondaries of current transformers located in multiple circuits and feeding the combined current into a conventional meter (this works only when the service voltages and ratios of the current transformers are identical)
- Using a multi-circuit meter, which accepts the voltage and current inputs from multiple services

Totalized demand is the sum of the *coincident* demands and is usually less than the sum of the individual peak demands registered by the individual meters. Totalized energy equals the sum of the energies measured by the individual meters.

Table 7.2 illustrates the effects of totalizing a customer served by three delivery (and metering) points. It presents the customer's demands over a period of four demand intervals and illustrates the difference in the maximum totalized demand compared to the sum of the individual meter maximum demands.

TABLE 7.2 Example of Totalized Meter Data

Interval	Meter A	Meter B	Meter C	Totalized (A+B+C)
1	**800**	600	700	*2100*
2	780	650	**740**	*2170*
3	750	**700**	500	*1950*
4	780	680	720	***2180***

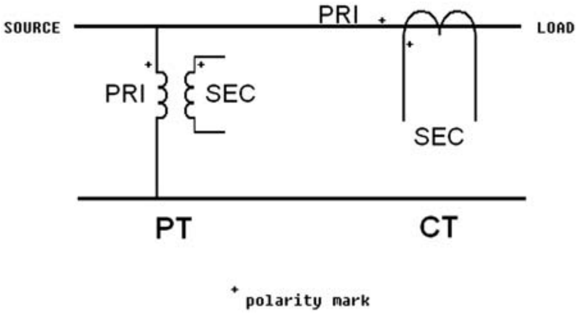


FIGURE 7.5 Instrument transformer symbols.

The peak kW demand for each meter point is shown in bold. The sum of these demands is 2240 kW. However, when summed interval-by-interval, the peak of the sums is 2180 kW. This is the *totalized demand*. The difference in the two demands, 60 kW, represents a cost savings to the customer. It should be clear why many customers with multiple service points desire to have their demands totalized.

Instrument Transformers

Instrument transformers is the general name for members of the family of current transformers (CTs) and voltage transformers (VTs) used in metering. They are high-accuracy transformers that convert load currents or voltages to other (usually smaller) values by some fixed ratio. Voltage transformers are also often called potential transformers (PTs). The terms are used interchangeably in this section. CTs and VTs are most commonly used in services where the current and/or voltage levels are too large to be applied directly to the meter.

A current transformer is rated in terms of its nameplate primary current as a ratio to five amps secondary current (e.g., 400:5). The CT is not necessarily limited to this nameplate current. Its maximum capacity is found by multiplying its nameplate rating by its *rating factor*. This yields the total current the CT can carry while maintaining its rated accuracy and avoiding thermal overload. For example, a 200:5 CT with a rating factor of 3.0 can be used and will maintain its rated accuracy up to 600 amps. Rating factors for most CTs are based on open-air outdoor conditions. When a CT is installed indoors or inside a cabinet, its rating factor is reduced.

A voltage transformer is rated in terms of its nameplate primary voltage as a ratio to either 115 or 120 volts secondary voltage (e.g., 7200:120 or 115000:115). These ratios are sometimes listed as an equivalent ratio to 1 (e.g., 60:1 or 1000:1).

Symbols for a CT and a PT connected in a two-wire circuit are shown in Fig. 7.5.

Measuring kVA

In many cases, a combination watthour demand meter will provide the billing determinants for small- to medium-sized customers served under rates that require only real power (kW) and energy (kWh). Rates for larger customers often require an *extended function* meter to provide the additional reactive or apparent power capability needed to measure or determine kVA demand. There are two common methods for determining kVA demand for billing.

1. **Actual kVA**. This method directly measures actual kVA, a simple matter for electronic meters.
2. **Average Power Factor kVA**. This method approaches the measurement of kVA in a more roundabout fashion. It was developed when most metering was done with mechanical meters that could directly measure only real energy and power (kWh and kW). With a little help, they could measure kvarh. Those few meters that could measure actual kVA were very complex and demanded frequent maintenance. The Average Power Factor (APF) method of calculating kVA addressed these limitations. It requires three (3) pieces of meter information:

- Total real energy(kWh)
- Maximum real demand(kW)
- Total reactive energy(kvarh)

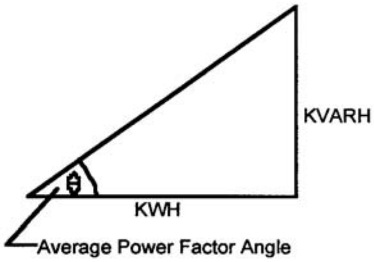
These can be measured with two standard mechanical meters. The first meter measures kWh and kW. With the help of a special transformer to shift the voltage signals 90° in phase, the second mechanical meter can be made to measure kvarh.

APF kVA is determined by calculating the customer's "average power factor" over the billing period using the total kWh and kvarh for the period. This APF is then applied to the maximum kW reading to yield APF kVA. An example of this calculation process follows.

Customer: XYZ Corporation

Billing determinants obtained from the meter:

kWh	981,600
kvarh	528,000
kW	1412



$$\tan(\theta) = \frac{KVARH}{KWH} = \frac{528000}{981600} = 0.5378$$

$$\theta = 28.275^{o}$$

$$APF = \cos(\theta) = 0.881$$

$$KVA\,\text{demand} = \frac{KW\text{ demand}}{APF} = \frac{1412}{0.881} = 1603\,\text{KVA}$$

FIGURE 7.6 Calculation of kVA demand using the Average Power Factor method.

Defining Terms

Class: The class designation of a watthour meter represents the maximum current at which the meter can be operated continuously with acceptable accuracy and without excessive temperature rise. Examples of common watthour meter classes are:

Self-contained — Class 200, 320, or 400
Transformer rated — Class 10 or 20

Test amperes (TA): The test amperes rating of a watthour meter is the current that is used as a base for adjusting and determining percent registration (accuracy). Typical test current ratings and their relations to meter class are:

Class 10 and 20 — TA 2.5
Class 200 — TA 30

Self-contained meter: A self-contained meter is one designed and installed so that power flows from the utility system *through* the meter to the customer's load. The meter sees the total load current and full service voltage.

Transformer rated meter: A transformer rated meter is one designed to accept *reduced* levels of current and/or voltage that are directly proportional to the service current and voltage. The primary windings of current transformers and/or voltage transformers are placed in the customer's service and see the total load current and full service voltage. The transformer rated meter connects into the secondary windings of these transformers.

Meter element: A meter element is the basic energy and power measurement circuit for one set of meter input signals. It consists of a current measurement device and a voltage measurement device for one phase of the meter inputs. Usually, a meter will have one less element than the number of wires in the circuit being metered. That is, a 4-wire wye or delta circuit will be metered by a 3-element meter; a 3-wire delta circuit will be metered by a 2-element meter, although there are numerous exceptions.

CT PT ratio: A number or factor obtained by multiplying the current transformer ratio by the potential transformer ratio. Example: If a meter is connected to 7200:120 volt PTs (60:1) and 600:5 CTs (120:1), the CT PT ratio is $60 \times 120 = 7200$. A metering installation may have current transformers but no potential transformer in which case the CT PT ratio is just the CT ratio.

Meter multiplier: Also called the dial constant or kilowatthour constant, this is the multiplier used to convert meter kWh readings to actual kWh. The meter multiplier is the CT PT ratio. For a self-contained meter, this constant is 1.

Further Information

Further information and more detail on many of the topics related to metering can be found in the *Handbook for Electricity Metering*, published by Edison Electric Institute. This authoritative book provides extensive explanations of many aspects of metering, from fundamentals of how meters and instrument transformers operate, to meter testing, wiring, and installation.

7.2 Basic Electric Power Utilization — Loads, Load Characterization and Load Modeling

Andrew Hanson

Utilization is the "end result" of the generation, transmission, and distribution of electric power. The energy carried by the transmission and distribution system is turned into useful work, light, heat, or a combination of these items at the utilization point. Understanding and characterizing the utilization of electric power is critical for proper planning and operation of power systems. Improper characterization of utilization can result of over or under building of power system facilities and stressing of system equipment beyond design capabilities. This section describes some of the basic concepts used to characterize and model loads in electric power systems.

The term *load* refers to a device or collection of devices that draw energy from the power system. Individual loads (devices) range from small light bulbs to large induction motors to arc furnaces. The term *load* is often somewhat arbitrarily applied, at times being used to describe a specific device, and other times referring to an entire facility and even being used to describe the lumped power requirements of power system components and connected utilization devices downstream of a specific point in large-scale system studies.

Basic Load Characterization

A number of terms are used to characterize the magnitude and intensity of loads. Several such terms are defined and uses outlined below.

Energy — Energy use (over a specified period of time) is a key identifying parameter for power system loads. Energy use is often recorded for various portions of the power system (e.g., homes, businesses, feeders, substations, districts). Utilities report aggregate system energy use over a variety of time frames (daily, weekly, monthly, and annually). System energy use is tied directly to sales and thus is often used as a measure of the utility or system performance from one period to another.

Demand — Loads require specific amounts of energy over short periods of time. Demand is a measure of this energy and is expressed in terms of power (kilowatts or Megawatts). Instantaneous demand is the peak instantaneous power use of a device, facility, or system. Demand, as commonly referred to in utility discussions, is an integrated demand value, most often integrated over 10, 15, or 30 min. Integrated demand values are determined by dividing the energy used by the time interval of measurement or the demand interval.

$$\text{Demand} = \frac{\text{Energy Use Over Demand Interval}}{\text{Demand Interval}} \tag{7.1}$$

Integrated demand values can be much lower than peak instantaneous demand values for a load or facility.

Demand Factor — Demand factor is a ratio of the maximum demand to the total connected load of a system or the part of the system under consideration. Demand factor is often used to express the expected diversity of individual loads within a facility prior to construction. Use of demand factors allows facility power system equipment to be sized appropriately for the expected loads.

$$\text{Demand Factor} = \frac{\text{Maximum Demand}}{\text{Total Connected Load}} \tag{7.2}$$

Load Factor — Load factor is similar to demand factor and is calculated from the energy use, the demand, and the period of time associated with the measurement.

$$\text{Load Factor} = \frac{\text{Energy Use}}{\text{Demand} \times \text{Time}} \tag{7.3}$$

A high load factor is typically desirable, indicating that a load or group of loads operates near its peak most of the time, allowing the greatest benefit to be derived from any facilities installed to serve the load.

Composite Loads and Composite Load Characterization

It is impractical to model each individual load connected to a power system to the level of detail at which power is delivered to each individual utilization device. Loads are normally lumped together to represent all of the “downstream” power system components and individual connected loads. This grouping occurs as a result of metering all downstream power use from a certain point in the power system, or as a result of model simplification in which effects of the downstream power system and connected loads are represented by a single load in system analysis.

Coincidence and Diversity

Although individual loads vary unpredictably from hour to hour and minute to minute, an averaging effect occurs as many loads are examined in aggregate. This effect begins at individual facilities (home, commercial establishment, or industrial establishment) where all devices are seldom if ever in operation at the same instant. Progressing from an individual facility to the distribution and transmission systems, the effect is compounded, resulting in somewhat predictable load characteristics.

Diversity is a measure of the dispersion of the individual loads of a system under observation over time. Diversity is generally low in individual commercial and industrial installations. However, at a feeder level, diversity is a significant factor, allowing more economical choices for equipment since the feeder needs to supply power to the aggregate peak load of the connected customers, not the sum of the customer individual (noncoincident) peak loads.

Groups of customers of the same class (i.e., residential, commercial, industrial) tend to have an aggregate peak load per customer that decreases as the number of customers increases. This tendency is termed *coincidence* and has significant impact on the planning and construction of power systems (Willis, 1997). For example, load diversity would allow a feeder or substation to serve a number of customers whose individual (noncoincident) peak demands may exceed the feeder or substation rating by a factor of two or more.

$$\text{Coincidence Factor} = \frac{\text{Aggregate Demand for a Group of Customers}}{\text{Sum of Individual Customer Demands}} \tag{7.4}$$

Note that there is a minor but significant difference between coincidence (and its representation as a coincidence factor) and the demand factor discussed above. The coincidence factor is based on the *observed* peak demand for individuals and groups, whereas the demand factor is based on the *connected* load.

Load Curves and Load Duration

Load curves and load duration curves graphically convey very detailed information about the characteristics of loads over time. Load curves typically display the load of a customer class, feeder, or other portion of a power system over a 24-hour period. Load duration curves display the cumulative amount of time that load levels are experienced over a period of time.

Load curves represent the demand of a load or groups of load over a period of time, typically 24 hours. The curves provide "typical" load levels for a customer class on an hour-by-hour or minute-by-minute basis. The curves themselves represent the demand of a certain class of customers or portion of the system. The area under the curve represents the corresponding energy use over the time period under consideration. Load curves provide easily interpreted information regarding the peak load duration as well as the variation between minimum and maximum load levels. Load curves provide key information for daily load forecasts allowing planners and operators to ensure system capacity is available to meet customer needs. Three sample load curves (for residential, commercial, and industrial customer classes) are shown in Fig. 7.7 through Fig. 7.9.

Load curves can also be developed on a feeder or substation basis, as a composite representation of the load profile of a portion of the system.

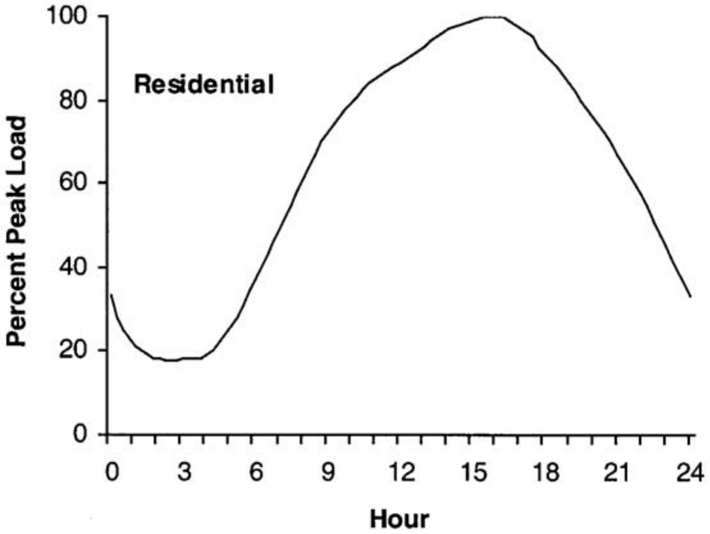


FIGURE 7.7 Residential load curve.

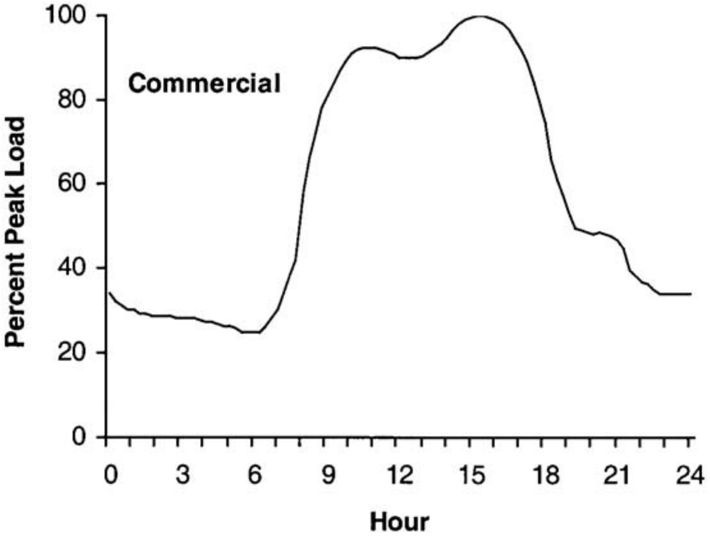


FIGURE 7.8 Commercial load curve.

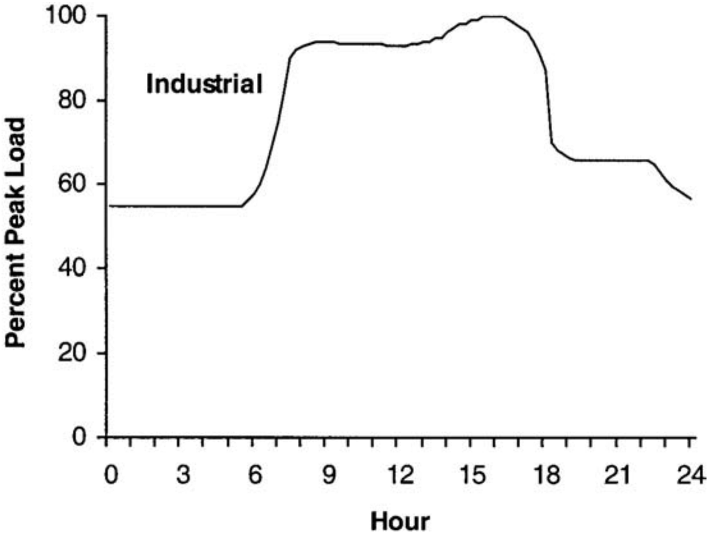


FIGURE 7.9 Industrial load curve.

Load duration curves quickly convey the duration of the peak period for a portion of a power system over a given period of time. Load duration curves plot the cumulative amount of time that load levels are seen over a specified time period. The information conveyed graphically in a load duration curve, although more detailed, is analogous to the information provided by the load factor discussed above. A sample load duration curve is shown in Fig. 7.10.

Load duration curves are often characterized by very sharp ascents to the peak load value. The shape of the remainder of the curves vary based on utilization patterns, size, and content of the system for which the load duration curve is plotted.

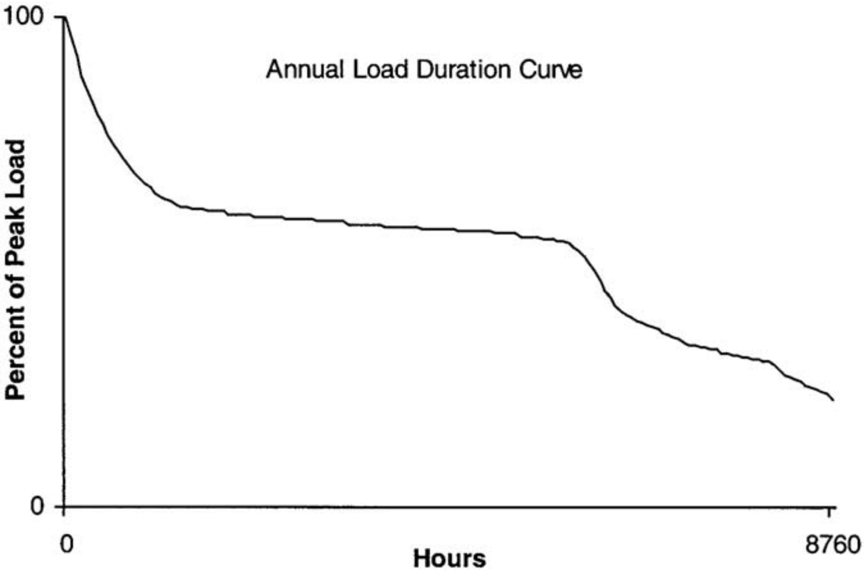


FIGURE 7.10 Annual load duration curve.

Composite Load Modeling

Load models can generally be divided into a variety of categories for modeling purposes. The appropriate load model depends largely on the application. For example, for switching transient analyses, simple load models as combinations of time-invariant circuit elements (resistors, inductors, capacitors) and/or voltage sources are usually sufficient. Power flow analyses are performed for a specific operating point at a specific frequency, allowing loads to be modeled primarily as constant impedance or constant power. However, midterm and extended term transient stability analyses require that load voltage and frequency dependencies be modeled, requiring more complex aggregate load models. Two load models are discussed below.

Composite loads exhibit dependencies on frequency and voltage. Both linear (Elgerd, 1982; Gross, 1986) and exponential models (Arrillaga and Arnold, 1990) are used for addressing these dependencies.

Linear Voltage and Frequency Dependence Model — The linear model provides excellent representation of load variations as frequency and voltages vary by small amounts about a nominal point.

$$P = P_{nominal} + \frac{\partial P}{\partial \left|\overline{V}\right|}\Delta\left|\overline{V}\right| + \frac{\partial P}{\partial f}\Delta f \tag{7.5}$$

$$Q = Q_{nominal} + \frac{\partial Q}{\partial \left|\overline{V}\right|}\Delta\left|\overline{V}\right| + \frac{\partial Q}{\partial f}\Delta f \tag{7.6}$$

where $P_{nominal}, Q_{nominal}$ are the real and reactive power under nominal conditions,

$\frac{\partial P}{\partial \left|\overline{V}\right|}, \frac{\partial P}{\partial f}, \frac{\partial Q}{\partial \left|\overline{V}\right|}, \frac{\partial Q}{\partial f}$ are the rates of change of real and reactive power with respect to voltage magnitude and frequency, and

$\Delta\left|\overline{V}\right|, \Delta f$ are the deviations in voltage magnitude and frequency from nominal values.

The values for the partial derivatives with respect to voltage and frequency can be determined through analysis of metered load data recorded during system disturbances or in the case of very simple loads, through calculations based on the equivalent circuit models of individual components.

Exponential Voltage and Frequency Dependence Model — The exponential model provides load characteristics useful in midterm and extended term stability simulations in which the changes in system frequency and voltage are explicitly modeled in each time step.

$$P = P_{\text{nominal}} \left|\overline{V}\right|^{pv} f^{\,pf} \tag{7.7}$$

$$Q = Q_{\text{nominal}} \left|\overline{V}\right|^{qv} f^{\,qf} \tag{7.8}$$

where P_{nominal}, Q_{nominal} are the real and reactive power of the load under nominal conditions

$|V|$ is the voltage magnitude in per unit

f is the frequency in per unit

pv, pf, qv, and qf are the exponential modeling parameters for the voltage and frequency dependence of the real and reactive power portions of the load, respectively

Other Load-Related Issues

Cold Load Pickup

Following periods of extended service interruption, the advantages provided by load diversity are often lost. The term *cold load pickup* refers to the energization of the loads associated with a circuit or substation following an extended interruption during which much of the diversity normally encountered in power systems is lost.

For example, if a feeder suffers an outage, interrupting all customers on the feeder during a particularly cold day, the homes and businesses will cool to levels below the individual thermostat settings. This situation eliminates the diversity normally experienced, where only a fraction of the heating will be required to operate at any given time. Once power is restored, the heating at all customer locations served by the feeder will attempt to operate to bring the building temperatures back to levels near the thermostat settings. The load experienced by the feeder following reenergization can be far in excess of the design loading due to lack of load diversity.

Cold load pickup can result in a number of adverse power system reactions. Individual service transformers can become overloaded under cold load pickup conditions, resulting in loss of life and possible failure due to overheating. Feeder load levels can exceed protective device ratings/settings, resulting in customer interruptions following initial service restoration. Additionally, the heavily loaded system conditions can result in conductors sagging below their designed minimum clearance levels, creating safety concerns.

Harmonics and Other Nonsinusoidal Loads

Electronic loads that draw current from the power system in a nonsinusoidal manner represent a significant portion of the load connected to modern power systems. These loads cause distortions of the generally sinusoidal characteristics traditionally observed. Harmonic loads include power electronic based devices (rectifiers, motor drives, switched mode power supplies, etc.) and arc furnaces. More details on power electronics and their effects on power system operation can be found in the power electronics section of this handbook.

References

Arrillaga, J. and Arnold, C. P., *Computer Analysis of Power Systems*, John Wiley & Sons, West Sussex, 1990.

Elgerd, O. I., *Electric Energy Systems Theory: An Introduction*, 2nd ed., McGraw Hill Publishing Company, New York, 1982.

Gross, C. A., *Power System Analysis,* 2nd ed., John Wiley & Sons, New York, 1986.

1996 National Electric Code, NFPA 70, Article 100, Batterymarch Park, Quincy, MA.

Willis, H. L., *Power Distribution Planning Reference Book,* Marcel-Dekker, Inc., New York, 1997.

Further Information

The references provide a brief treatment of loads and their characteristics. More detailed load characteristics for specific industries can be found in specific industry trade publications. For example, specific characteristics of loads encountered in the steel industry can be found in Fruehan, R. J., Ed., *The Making, Shaping and Treating of Steel*, 11th ed., AISE Steel Foundation, Pittsburgh, Pennsylvania, 1998.

The quarterly journals *IEEE Transactions on Power Systems* and *IEEE Transactions on Power Delivery* contain numerous papers on load modeling, as well as short and long term load forecasting. Papers in these journals also track recent developments in these areas.

Information on load modeling for long term load forecasting for power system planning can be found the following references respectively:

Willis, H. L., *Spatial Electric Load Forecasting*, Marcel-Dekker, Inc., New York, 1996.

Stoll, H. G., *Least Cost Electric Utility Planning*, John Wiley & Sons, New York, 1989.

7.3 Electric Power Utilization: Motors

Charles A. Gross

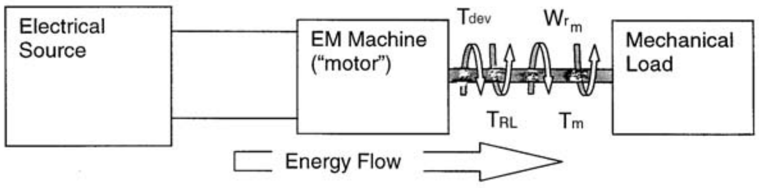
A major application of electric energy is in its conversion to mechanical energy. Electromagnetic, or "EM" devices designed for this purpose are commonly called "motors." Actually the machine is the central component of an integrated system consisting of the source, controller, motor, and load. For specialized applications, the system may be, and frequently is, designed as a integrated whole. Many household appliances (e.g., a vacuum cleaner) have in one unit, the controller, the motor, and the load. However, there remain a large number of important stand-alone applications that require the selection of a proper motor and associated control, for a particular load. It is this general issue that is the subject of this section.

The reader is cautioned that there is no "magic bullet" to deal with all motor-load applications. Like many engineering problems, there is an artistic, as well as a scientific dimension to its solution. Likewise, each individual application has its own peculiar characteristics, and requires significant experience to manage. Nevertheless, a systematic formulation of the issues can be useful to a beginner in this area of design, and even for experienced engineers faced with a new or unusual application.

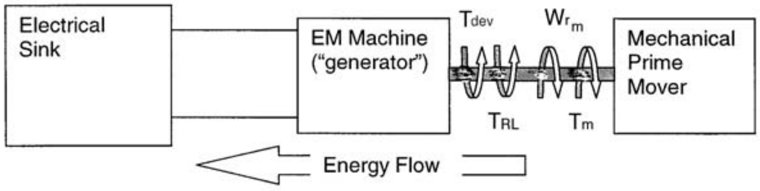
Some General Perspectives

Consider the general situation in Fig. 7.11a. The flow of energy through the system is from left to right, or from electrical source to mechanical load. Also, note the positive definitions of currents, voltages, speed, and torques. These definitions are collectively called the "motor convention," and are logically used when motor applications are under study. Likewise, when generator applications are considered, the sign conventions of Fig. 7.11b (called generation convention) will be adopted. This means that variables will be positive under "normal" conditions (motors operating in the motor mode, generators in the generator mode), and negative under some abnormal conditions (motors running "backwards," for example). Using motor convention:

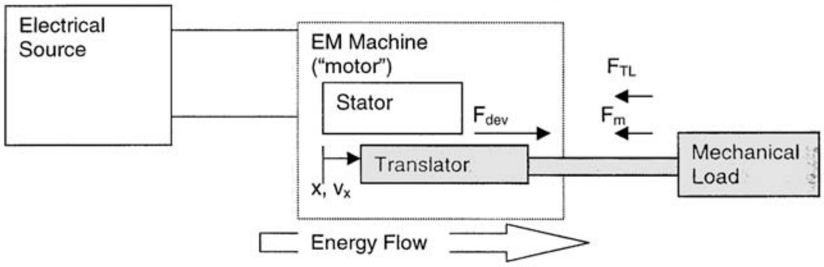
$$T_{dev} - \left(T_m + T_{RL}\right) = T_{dev} - T'_m = J\left(d\omega_{rm}/dt\right) \tag{7.9}$$



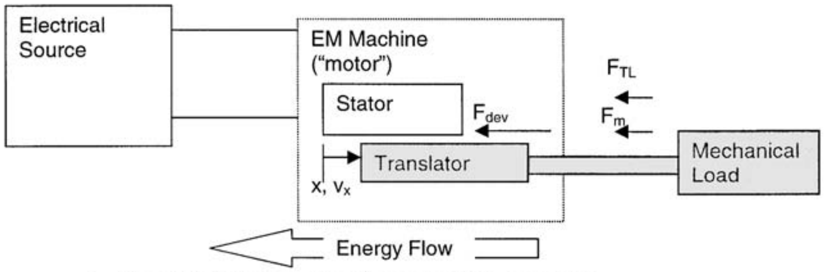
a. the EM rotational machine; motor convention



b. the EM rotational machine; generator convention



c. the EM translational machine; motor convention



d. the EM translational machine; generator convention

FIGURE 7.11 Motor and generator sign conventions for EM machines.

where T_{dev} = EM torque, produced by the motor, Nm
T_m = torque absorbed by the mechanical load, including the load losses and that used for useful mechanical work, Nm
T_{RL} = rotational loss torque, internal to the motor, Nm
$T'_m = T_m + T_{RL}$ = equivalent load torque, Nm
J = mass polar moment of inertia of all rotating parts, kg-m^2
ω_{rm} = angular velocity of rotating parts, rad/s

Observe that whenever $T_{dev} > T'_m$, the system accelerates; if $T_{dev} < T'_m$, the system decelerates. The system will inherently seek out the equilibrium condition of $T_{dev} = T'_m$, which will determine the running speed. In general, the steady state running speed for any motor-load system occurs at the intersection of the motor and load torque-speed characteristics, i.e., where $T_{dev} = T'_m$. If $T_{dev} > T'_m$, the system is accelerating; for $T_{dev} < T'_m$, the system decelerates. Thus, torque-speed characteristics for motors and loads are necessary for the design of a speed (or position) control system.

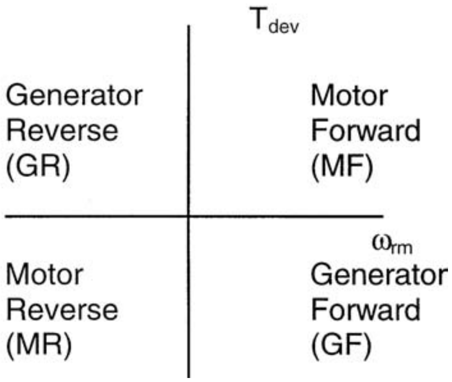


FIGURE 7.12 Operating modes.

The corresponding system powers are:

$P_{dev} = T_{dev}\ \omega_{rm}$= EM power, converted by the motor into mechanical form, W
$P_m = T_m\ \omega_{rm}$= power absorbed by the mechanical load, including the load losses and that used for useful mechanical work, W
$P_{RL} = T_{RL}\ \omega_{rm}$= rotational power loss, internal to the motor, W

Operating Modes

Equation (7.9) implies that torque and speed are positive. Consider positive speed as "forward," meaning rotation in the "normal" direction, which should be obvious in a specific application. "Reverse" is defined to mean rotation in the direction opposite to "forward," and corresponds to $\omega_{rm} < 0$. Positive EM torque is in the positive speed direction. Using motor convention, first quadrant operation means that (1) speed is positive ("forward") and (2) T_{dev} is positive (also forward), and transferring energy from motor to load ("motoring"). There are four possible operating modes specific to the four quadrants of Fig. 7.12. In any application, a primary consideration is to determine which of these operating modes will be required.

Motor, Enclosure, and Controller Types

The general types of enclosures, motors, and controllers are summarized in Tables 7.3, 7.4, and 7.5.

System Design

The design of a proper motor-enclosure-controller system for a particular application is a significant engineering problem requiring engineering expertise and experience. The following issues must be faced and resolved.

Load Requirements

1. The steady-state duty cycle with torque-speed (position) requirements at each load step.
2. What operating modes are required.
3. Dynamic performance requirements, including starting and stopping, and maximum and minimum accelerations.
4. The relevant torque-speed (position) characteristics.
5. All load inertias (J).
6. Coupling options (direct drive, belt-drive, gearing).
7. Reliability of service. How critical is a system failure?
8. Future modifications.

Environmental Requirements

1. Ambient atmospheric conditions (pressure, temperature, humidity, content)
2. Indoor, outdoor application
3. Wet, dry location
4. Ventilation
5. Acceptable acoustical noise levels
6. Electrical/mechanical hazards to personnel
7. Accessibility for inspection and maintenance

Electrical Source Options

1. DC-AC
2. If AC, single- and/or three-phase
3. Voltage level
4. Frequency
5. Capacity (kVA)
6. Protection options
7. Power quality specifications

Preliminary System Design

Based on the information compiled in the steps above, select an appropriate enclosure, motor type, and controller. In general, the enclosure entries, reading from top to bottom in Table 7.3, are from simplest (and cheapest) to most complex (and expensive). Select the simplest enclosure that meets all the environmental constraints. Next, select a motor and controller combination from Tables 7.4 and 7.5. This requires personal experience and/or consulting with engineers with experience relevant to the application.

TABLE 7.3 General Enclosure Types[a]

Types
Open
Drip-proof
Splash-proof
Semi-guarded
Weather protected
Type I
Type II
Totally enclosed
Nonventillated
Fan-cooled
Explosion-proof
Dust-ignition-proof
Water-proof
Pipe-ventilated
Water-cooled
Water-air-cooled
Air-to-air-cooled
Air-over-cooled

[a] See NEMA Standard MG 1.1.25-1.1.27 for definitions.

In general, DC motors are expensive and require more maintenance, but have excellent speed and position control options. Single-phase AC motors are limited to about 5 kW, but may be desirable in locations where three-phase service is not available and control specifications are not critical.

Three-phase AC synchronous motors are not amenable to frequent starting and stopping, but are ideal for medium and high power applications which run at essentially fixed speeds. Three-phase AC cage rotor induction motors are versatile and economical, and will be the preferred choice for most applications, particularly in the medium power range. Three-phase AC wound rotor induction motors are expensive, and only appropriate for some unusual applications.

The controller must be compatible with the motor selected; the best choice is the most economical that meets all load specifications. If the engineer's experience with the application under study is lacking, two or more systems should be selected.

System Ratings

Based on the steps above, select appropriate power, voltage, and frequency ratings. For cyclic loads, the power rating may tenatively be selected based on the "rms horsepower" method (calculating the rms power requirements over the load cycle).

System Data Acquisition

Request data from at least two vendors on all systems selected in the steps above, including:

- circuit diagrams
- performance test data
- equivalent circuit values, including inertia constants
- cost data
- warranties and guarantees

TABLE 7.4 General Motor Types[a]

Type
DC motors (commutator devices)
Permanent magnet field
Wound field
Series
Shunt
Compound
AC motors
Single-phase
Cage rotor
Split phase
Resistance-start
Capacitor start
Single capacitor (start-run)
Capacitor start/capacitor run
Shaded pole
Wound rotor
Repulsion
Repulsion start/induction run
Universal
Synchronous
Hysteresis
Three-phase
Synchronous
Permanent magnet field
Wound field
Induction
Cage rotor
NEMA Design A,B,C,D,F
Wound rotor

[a] See NEMA Standard MG 1.1.1-1.1.21 for definitions.

Engineering Studies

Perform the following studies using data from the system data acquisition step above.

1. Steady state performance. Verify that each candidate system meets all steady state load requirements.
2. Dynamic performance. Verify that each system meets all dynamic load requirements.
3. Load cycle efficiency. Determine the energy efficiency over the load cycle.
4. Provide a cost estimate for each system, including capital investment, maintenance, and annual operating costs.
5. Perform a power quality assessment.

Based on these studies, select a final system design.

Final System Design

Request a competitive bid on the final design from appropriate vendors. Select a vendor based on cost, expectation of continuing technical support, reputation, warranties, and past customer experience.

Field Testing

Whenever practical, customer and vendor engineers should design and perform field tests on the installed system, demonstrating that it meets or exceeds all specifications. If multiple units are involved, one proto-unit should be installed, tested, and commissioned before delivery is made on the balance of the order.

TABLE 7.5 General Motor Controllers

Type
DC motor controllers
Electromechanical
Armature starting resistance; rheostat field control
Power electronic drive
Phase converters: 1, 2, 4 quadrant drives
Chopper control: 1, 2, 4 quadrant drives
AC motor controllers
Single-phase
Electromechanical
Across-the-line: protection only
Step-reduced voltage
Power electronic drive
Armature control: 1, 2, 4 quadrant drives
Three-phase induction
Cage rotor
Electromechanical
Across-the-line: protection only
Step-reduced voltage
Power electronic drive (ASDs)
Variable voltage source inverter
Variable current source inverter
Chopper voltage source inverter
PWM voltage source inverter
Vector control
Wound rotor
Variable rotor resistance
Power electronic rotor power recovery
Three-phase synchronous
Same as cage rotor induction
Brushless DC control

Further Information

The design of a properly engineered motor-controller system for a particular application requires access to several technical resources, including standards, the technical literature, manufacturers' publications, textbooks, and handbooks. The following section provides a list of references and resource material that the author recommends for work in this area. In many cases, more recent versions of publications listed are available and should be used.

Organizations

American National Standards Institute (ANSI), 1430 Broadway, New York, NY 10018.
Institute of Electrical and Electronics Engineers (IEEE), 445 Hoes Lane, Piscataway, NJ 08855.
International Organization for Standardization (ISO) 1, rue de Varembe, 1211 Geneva 20, Switzerland.
American Society for Testing and Materials (ASTM), 1916 Race Street, Philadelphia, PA 19103.
National Electrical Manufacturers Association (NEMA), 2101 L Street, NW, Washington, D.C. 20037.
National Fire Protection Association (NFPA), Batterymarch Park Quincy, MA 02269.
The Rubber Manufacturers Association, Inc., 1400 K Street, NW, Suite 300, Washington, D.C. 20005.
Mechanical Power Transmission Association, 1717 Howard Street, Evanston, IL 60201.

Standards

NEMA MG 1-1987, *Motors and Generators.*

NEMA MG 2-1983, *Safety Standard for Construction and Guide for Selection, Installation and Use of Electric Motors and Generators.*

NEMA MG 3-1984, *Sound Level Prediction for Installed Rotating Electrical Machines.*

NEMA MG 13-1984, *Frame Assignments for Alternating-Current Integral-horsepower Induction Motors.*

ANSI/NFPA 70-1998, *National Electrical Code.*

IEEE Std 1-1969, *General Principles for Temperature Limits in the Rating of Electric Equipment.*

IEEE Std 85-1980, *Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery.*

ANSI/IEEE Std 100-1984, *IEEE Standard Dictionary of Electrical and Electronics Terms.*

IEEE Std 112-1984, *Standard Test Procedure for Potyphase Induction Motors and Generators.*

IEEE Std 113-1985, *Guide on Test Procedures for DC Machines.*

ANSI/IEEE Std 114-1984, *Test Procedure for Single-Phase Induction Motors.*

ANSI/IEEE Std 115-1983, *Test Procedures for Synchronous Machines.*

ANSI/IEEE Std 117-1985, *Standard Test Procedure for Evaluation of Systems of Insulating Materials for Random-Wound AC Electric Machinery.*

ANSI/IEEE Std 304-1982, *Test Procedure for Evaluation and Classification of Insulation Systems for DC Machines.*

ISO R-1000, *SI Units and Recommendations for the Use of their Multiples and of Certain Other Units.*

Books (an abridged sample)

Acarnley, P. P., *Stepping Motors,* 2nd ed., Peter Peregrinus, Ltd., London, 1984.

Anderson, L. R., *Electric Machines and Transformers,* Reston Publishing, Reston, VA, 1981.

Bergseth, F. R. and Venkata, S. S., *Introduction to Electric Energy Devices,* Prentice-Hall, Englewood Cliffs, NJ, 1987.

Brown, D. and Hamilton 111, E. P., *Electromechanical Energy Conversion,* Macmillan, New York, 1984.

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